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14. ABSTRACT
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Grazing Angle Proton Scattering: Effects on Chandra and XMM-Newton X-Ray Telescopes

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Abstract—**A proton scattering process resulted in damage to one of the Chandra X-ray telescope's focal plane detectors. In this process, incident protons were transmitted, by scattering off the telescope mirrors, to the focal plane. We identify the proton population responsible for the damage and, using a proper grazing angle formalism, we show that the standard calculations of grazing angle scattering will significantly under predict the expected proton flux at the focal plane.**

Index Terms—**Chandra X-ray telescope CCD radiation damage.**

I. Introduction

SEVERAL weeks into the Chandra X-ray telescope mission, unexpected damage was observed to one of its cameras [1]. The problem was identified as radiation damage to the front illuminated charge coupled detectors (CCD) the advanced CCD imaging spectrometer (ACIS). The amount of damage was orders of magnitude larger than was to be expected this early in the mission. This event resulted in intensive study of the transmission of protons through the Chandra and the European XMM-Newton X-ray telescopes [2] using the Monte Carlo computer code Geant4 [3]. Both of these instruments utilize grazing incidence mirrors to focus the X-rays onto the CCD cameras in the focal plane.

In this paper, we will identify the particle population responsible for the damage and show that the transmission calculations of [2] use a model of proton scattering beyond its range of validity, leading to a significant underprediction of the transmission probability. We will present grazing angle scattering data and calculations and compare them to results computed using the same methods as are used in Geant4. Finally, we will discuss the effect that correct calculation of grazing angle scattering has on the calculated fluxes that reach the Chandra and XMM focal planes and suggest a way of obtaining more accurate results.

II. Radiation Damage to CCDs on Chandra

Energy loss in Si solid state detectors, such as CCDs falls into two classes ionizing and nonionizing energy loss (NIEL). Ionizing energy loss is due to the distant collisions of the incident particles with the conduction band electrons in the target material. This type of process leads to temporary damage that can be reversed with time or by annealing the material. The NIEL process consists of collisions with the nuclei in the material lattice. Any such collision that results in the energy transfer greater than about 30 keV can knock the target atom from its location in the lattice. The result of this collision, one atom in an interstitial location and one vacancy in the lattice, is called a Frankel defect and is the most common type of bulk damage. Frankel defects act as charge carrier traps, removing electrons from the charge collection process. Protons with energy above a few keV have sufficient energy to cause this defect. The probability of causing the defect increases with energy up to about 100 keV and then decreases with increasing energy with an energy dependence of 1/E [4].

The ACIS configuration of its 10 CCDs is shown in Fig. 1. Eight of the CCDs are front illuminated (FI), with the charge transfer gate region directly exposed to incident particles transmitted through the grazing optics of the telescope. Two are back illuminated (BI) and have the body of the device shielding the gate region. ACIS operates with a thin Polyamide film, with a light blocking aluminum coating upstream of the CCDs. The total mass density of the film and aluminum is sufficient to stop protons with $E < 80$ keV. During the first few weeks of the mission, the FI CCDs suffered a degradation of performance. The measure of the small inefficiency in transferring electrons from one pixel to another during the readout cycles, or charge transfer inefficiency (CTI), was increasing far more rapidly than expected for the FI CCDs. The CTI for the BI CCDs remained unchanged. The ACIS CCD integral proton fluence computed for the Chandra orbit is shown in Fig. 2. Our calculations assume that the incident proton population has an access path to the CCDs that does not degrade its spectral shape. We will justify this in Section IV. Electron fluences are not a concern because the low energy electrons ($E < 100$ keV) are swept away by the ACIS broom magnets and the higher energy electrons are both far less numerous and are highly inefficient producers of Frankel defects. The FI CCDs can be divided into Region A, the same length as BI CCDs, and remainder, Region B. Both BI and FI region A are sensitive to flux $f_A = 1.65 \times 10^7$ protons/cm^2-s corresponding to $E > 80$ keV. The region B, however is only sensitive to $f_B = 2.37 \times 10^4$ protons/cm^2-s corresponding to $E > 1,900$ keV). Since the ratio $f_B/f_A = 1.4 \times 10^{-3}$, the damage to the bulk silicon in region B is small compared to region A and can be neglected. Taking into account the fact the BI CCDs did not suffer any degradation it is likely that the damage occurred near the front of the devices. This is made more evident

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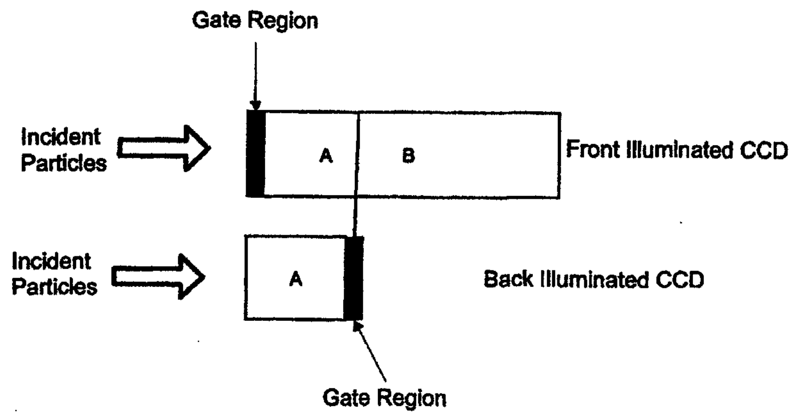

Fig. 1. Configuration of the front and back illuminated CCDs in the Chandra instrument focal plane. Region A corresponds to the first 45 μm of Si facing the incident particles. Back illuminated device gate region is shielded from transmitted protons by the upstream region A. Front illuminated devices do not have such shielding.

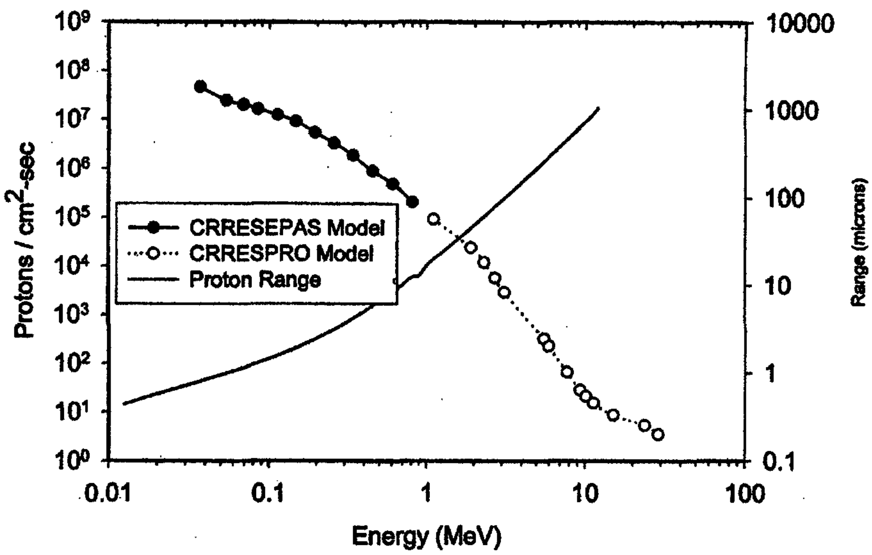

Fig. 2. Integral proton fluence and range in Si plotted as a function of energy. Proton models are described in [5].

by computing ⟨R⟩, the average range of protons in Si, weighted by the incident particle flux f(E)

$$\langle R\rangle = \frac{\int R(E)f(E)\,dE}{\int f(E)\,dE} \quad (1)$$

where R(E) is the proton range [6]. The computed value is $\langle R\rangle = 4.8\ \mu$m and most of the incident protons will stop within 4.8 μm of surface, in or near the highly sensitive gate region. This distance corresponds to the range of a 300 keV proton, thus all protons with $E < 300$ keV will deposit their full energy in the gate region, protons with $E = 400$ keV will deposit 315 keV and the much less numerous 2 MeV protons, 130 keV. Thus, if the external protons have access to the CCDs, the bulk of the damage will occur in the first few microns. This is verified by the work of one group [7] that has directly linked CTI increase to damage to the buried channel component of the CCD, located a fraction of a micron beneath the gate region.

We have shown that if the external protons have direct access to the CCDs, the population with energies in the range of 100–500 keV is responsible for the damage of the FI CCDs. In the next section will show how the proton transmission from outside the spacecraft to the CCDs takes place.

III. Standard Calculational Methods

The XMM team has used the Monte Carlo code Geant4 to calculate the proton transmission probability. We have chosen to use to use another well-established Monte Carlo code, MCNPX [8] to treat energetic proton scattering. Both Geant4 and MCNPX use condensed collision physics to compute the energy loss and angular scattering of a particle by considering the incident proton's collisions with atomic electrons and with atomic nuclei. Geant4 uses a "mixed" multiple scattering algorithm [3] to predict proton energy loss and scattering angle, while the MCNPX physics for determination of angular deflections is based on Rossi's Gaussian model [9], and in the energy range of interest here, a continuous-slowing-down energy loss model. In both Geant4 and MCNPX models, more numerous collisions with electrons result in small angular scattering and a small energy loss per collision. Less frequent collisions with target nuclei result in comparatively large scattering angles and

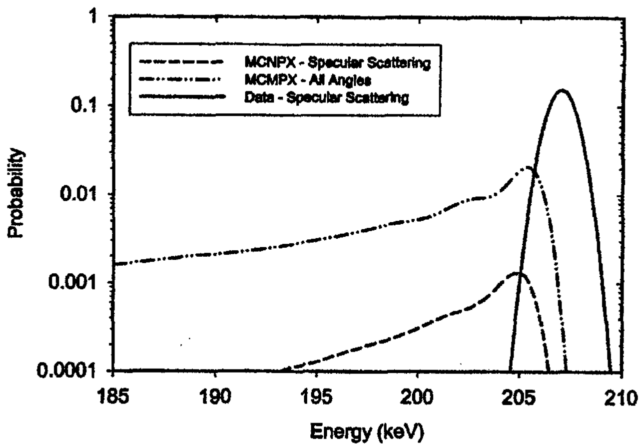

Fig. 3. Energy distributions of scattered 210 keV protons (aluminum target). Data curve is extracted from Winter *et al.* [12]. Specular scattering is for angle of incidence of 0.5°. "All angles" is for scattering between 0° and 90°.

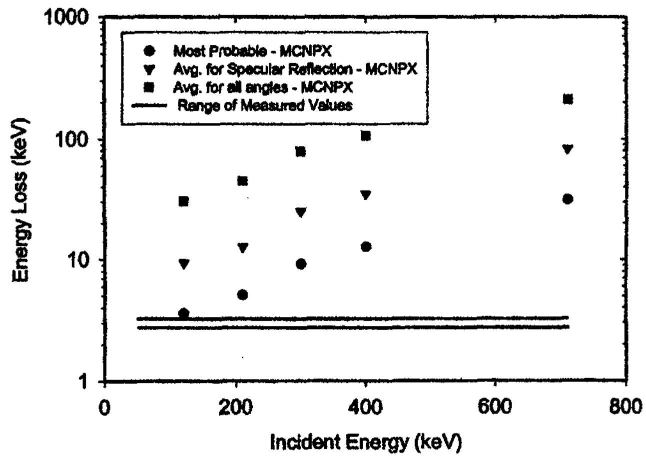

Fig. 4. Comparison of measured and computed energy loss of grazing incidence protons (aluminum target) as a function of incident energy. Measured most probable energy loss values [12] are all in the region between the two horizontal lines (all values were approximately 3 keV in the energy range of 50 to 710 keV). Due to the symmetry of the measured energy loss distributions [13], the measured most probable value is very close to the average value.

energy losses. Each collision in this approach is considered to be independent of the others and it is the sum of all the small, random changes in angle and energy that accounts for the final incident particle scattering angle and degraded energy.

These procedures, and their underlying physics models, were initially developed for thin foil and bulk material scattering of protons and alpha particles [10]. While these scattering models are valid for moderately large angles of incidence, or cases where the incident particle is traveling in the bulk material, the fundamental assumption of independence of the collisions is not valid for grazing angles of incidence. In addition, the assumption that the incident particle will enter into the bulk material, if the particle trajectory is not exactly parallel with respect to the surface, is also not valid. In the next section we will present a conceptually correct way to handle grazing incidence beam-target interactions.

IV. Grazing Angle Scattering

A. Energy Loss

In the past decade, grazing angle angular specular and near specular scattering has been studied as a means of deducing the properties of the scattering surface. Song and Wang [11] computed trajectories of grazing incidence protons incident on a carbon surface. Their work showed that, in general, the incident particles traveled only through the electron plasma cloud outside the surface before being reflected (no collisions with atomic nuclei). Furthermore, the lengths of trajectories inside the plasma cloud were only weakly dependent on the energy and angle of incidence. This result provides an explanation for the experimental results obtained by Winter *et al.* [12] and Pfanzender and Stolzle [13] that the most probable energy loss for a wide range of energies $30 < E < 710$ keV is of the order of 3 keV and does not depend on the angle of incidence. In addition, the energy spectra of the reflected protons are dominated by a Gaussian peak, centered on the most probable energy loss, with only small probabilities for greater energy losses.

Standard approach to scattering calculations cannot reproduce the effect of grazing angle trajectories that are reflected before striking the surface material. The differences between the two approaches are evident in Fig. 3. In this figure, the measured energy spectrum of 210 keV protons scattered off aluminum [12] is shown along with the results from an MCNPX calculation. As expected the MCNPX results have broad, low energy tail from the numerous high energy loss collisions with the atomic nuclei in the target material. A comparison of calculated and measured energy losses for protons incident on aluminum as a function of incident energy is shown in Fig. 4. The MCNPX calculated values show a much larger energy losses than the data. The agreement is even worse when the measured most probable values, which are very nearly average values, are compared to MCNPX average values. The effect of using the standard model of scattering when treating grazing angle scattering is the prediction of energy loss distributions that are highly asymmetric and very broad. This is true for MCNPX and the for the methods used in Geant4. The overall effect is for codes like MCNPX and Geant4 to predict larger energy losses than actually occur in the scattering process.

B. Angular Scattering

Angular scattering of the grazing incidence protons cannot be reproduced by the physics models used in Geant4 and MCNPX. These models assume that the proton does not react with the scattering surface until it enters and then is scattered as if it were traversing bulk material. In fact, the work of Song and Wang [11] shows the incident proton interacts with the surface long before it strikes it. In some cases the proton is reflected before it strikes the surface. For larger angles of incidence, the proton only enters the electron cloud that extends into the vacuum to a distance of a few nanometers out from the material surface. In general, for grazing angle scattering, the incident protons do not enter the bulk material at all.

The angular scattering of grazing angle incidence protons from a flat surface is dominated by a process with: 1) an energy loss small compared to the incident energy and 2) angular scattering characterized by weak interaction with the electron

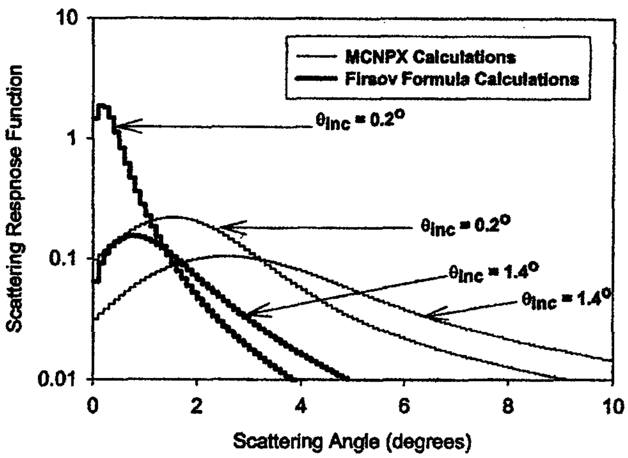

Fig. 5. Angular scattering distributions of 120 keV protons incident on aluminum calculated using MCNPX and Firsov distributions for two angles of incidence.

plasma cloud. In this case the proper scattering response is that given by Firsov [14]

$$N(\psi,\theta) = \frac{3}{2\pi\psi}\frac{(\psi\theta)^{3/2}}{\psi^3+\theta^3} \tag{2}$$

where N is the scattering response function, i.e., particle fraction per unit angle exiting the surface, ψ is the angle of incidence, and θ is the scattering angle. Note that the results are independent of the properties of both the scattering medium and the incident particle. Firsov's formula was derived in the limit of zero scattering energy loss and is independent of the precise form of scattering law as long as small angle scattering predominates. Both conditions are met in the case of grazing angle scattering. It is easy to show that the scattering function N peaks at $\psi = \theta$ (specular reflection) for all angles of incidence and that N is sharply peaked for small values of ψ and spreads out as ψ increases. Angular scattering curves, calculated both using MCNPX and (2), for two values of ψ are shown plotted in Fig. 5. Given that the vertical scale in Fig. 5 is logarithmic, it is evident, that the MCNPX distributions are much broader and have a much larger average scattering angle than the Firsov curves.

The consequence of MCNPX predicted distributions being too broad and being centered on the wrong angles is that the computation of transmission through the telescope mirrors will lead to a too low result. In reality, grazing incidence protons undergo nearly specular reflection and, behaving very much like X-rays, are efficiently focused onto the CCDs in the focal plane. The MCNPX and Geant4 scattering calculations predict that the protons will be largely dispersed by the mirrors and will strike some other component of the telescope and be absorbed.

V. Conclusion

This paper has focused on scattering on aluminum rather than the mirror materials. This is due to the lack of availability of data for the mirror materials. However, the overall grazing scattering results depend only weakly on the scattering surface properties and will not change significantly for the mirror materials.

MCNPX and Geant4 calculations underestimate the effect of protons on focal plane instruments for two reasons.

1) The codes will overestimate the energy loss of protons, thus shifting to the spectrum of transmitted protons to a higher incident energy. This effectively reduces the calculated number of protons reaching the focal plane instruments since the magnetospheric incident proton spectrum in falls off rapidly with energy.
2) The codes will calculate too large scattering angles thus directly decreasing the number of transmitted protons.

The ideal solution would to add the proper treatment of grazing angle scattering to the MCNPX and Geant4 codes. However, this may be a very major task and not easily accomplished. A good way of computing the upper limit of proton fluence in the focal plane is to assume that the protons undergo specular scattering with no energy loss, in effect they behave like photons. This approach will lead to only a slight overestimation of focal plane fluences.

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